

Post-LHC Accelerator Magnets

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Abstract—The design and practicality of future accelerators, such as hadron colliders and neutrino factories being considered to supercede the LHC, will depend greatly on the choice of superconducting magnets. Various possibilities will be reviewed and discussed, taking into account recent progress and projected improvements in magnet design and conductor development along with the recommendations from the 2001 Snowmass workshop.

Index Terms—Accelerator magnets, colliders, Nb₃Sn, superconducting magnets.

I. INTRODUCTION

WITH construction of the Large Hadron Collider well underway, a fraction of the community not directly involved is now directing its attention towards the next step beyond. This summer, the future of high-energy physics was discussed during a three-week workshop held in Snowmass, Colorado. The topics ranged from general physics to discussions on the latest tunneling technologies. A broad range of possible accelerators was investigated, including linear colliders, muon collider/neutrino factories and a next-generation hadron collider, generically known as the Very Large Hadron Collider or VLHC. Detailed discussion of these proposals can be found in the Snowmass proceedings [1].

While recognizing the challenges inherent in development of magnets for linear colliders, this paper will focus on magnet technology for circular colliders, which are not only challenging with respect to their performance requirements but where cost is a driving issue as well. There is an intrinsic expectation to reduce the cost per tesla-meter by at least a factor of two compared to the SSC dipoles. Coupled with heightened fiscal constraints and the natural trend for hadron colliders to become larger and larger, the cost issue becomes dominant. Reasonable solutions to this problem can only be accomplished by challenging convention. New technologies and designs need to be developed. The magnet working group at Snowmass reviewed and discussed the issues and challenges of a wide range of magnet technologies; these include superconducting magnets using NbTi, Nb₃Sn and

HTS conductor with fields ranging from 2 to 15 tesla and permanent magnets up to 4 tesla. The development time for

the various technology options varies significantly, but all are considered viable, providing an unprecedented variety of choice that can be determined by a balance of cost and application requirements. This paper will summarize some of these options and discuss the issues involved.

II. CURRENT STATUS

The LHC project, in which a large fraction of the accelerator magnet community is currently engaged, is on the verge of letting contracts for the main dipoles. These magnets represent the nadir of the application of NbTi, operating at 1.9 K with an operating field of 8.35 tesla [2]. RHIC is in operation as yet another example of industrially mass-produced superconducting magnets, but with the unique feature of having only cold-tested a fraction prior to installation [3]. The combination of these two projects defines the starting point for discussion of post-LHC magnet development.

A. Future Accelerators

Magnet applications for future accelerators come in two major categories; upgrades of existing facilities such as the LHC and Tevatron, and new facilities. With the constant drive for higher energy machines, there is a premium for achieving the highest field magnet possible in an upgrade scenario. In the case of a new facility, the parameters are much more open. Issues such as tunneling, cryo systems, logistics and location are important considerations in addition to magnet performance and cost.

B. Magnet Issues

The magnet requirements for the various machines generate some common issues. Cost is a pervasive consideration, but it prevails in the case of dipoles for the VLHC. Some cost issues include magnet length, aperture, conductor efficiency, and complexity. In terms of the next large-scale application of magnet technology, there is an implicit goal to reduce the cost per tesla-meter by at least a factor of two relative to the SSC dipoles. Conventional approaches have reached an asymptote, and meeting expectations on cost reduction demand consideration of alternate magnet designs and technologies. Smaller-scale applications, such as IR quads for both linear and hadron colliders, have operational requirements that demand very high performance levels. In these cases, cost is not a significant factor. During the

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Snowmass Workshop many design options and issues related to cost and performance were identified. Some examples are:

1) *Magnet length*

By reducing the number of magnets and hence the number of expensive interfaces, increasing the magnet length has clear cost saving advantages. The issues involved (which can be studied only by building magnets) are: mechanical stability and alignment, transport and magnetic measurements. The possibility of photon stops will also be a factor in the cost vs. length issue.

2) *Coldmass design*

Several magnet geometries have been presented, but a lot of work, integrated with input from accelerator physicists, is required to evaluate all the options and choose the right combination of cost and performance.

3) *Aperture*

With higher energy machines there is a trend towards smaller apertures. Cost savings come from a reduction in the amount of conductor required for a given field and support structure. Eliminating beam screens which take up precious aperture and dealing with beam instabilities are the challenges.

4) *Support systems (cryo, quench protection, etc.)*

Designing magnets that do not require complex support systems has obvious cost saving potential. Helium inventory, heat loads, warm- vs cold-iron designs, quench protection requirements (active vs passive), and copper current density are all topics for intensive study.

5) *Large scale production and testing*

Large scale, industrial production is an absolute necessity when considering fabrication of thousands of magnets. Significant R&D effort is necessary to provide manufacturable designs. Past experience has demonstrated a lack of sufficient consideration of the value of robust mechanical designs at the end of the R&D program. Both SSC and LHC magnet designs were not adequately prepared for industrial fabrication until late in the procurement process, leading to higher than necessary contingencies.

6) *Field quality*

Cable size control during heat treatment process for Nb₃Sn, cross-section designs that reduce persistent current effects and extending dynamic range (iron saturation control) are a few of the issues needing study.

New concepts that address these issues were presented at the Workshop. These concepts, along with some of the activities of other groups around the world, are summarized below.

III. CONDUCTOR DEVELOPMENT

Conductor is the cornerstone of superconducting magnet performance. At present, accelerator magnet technology is

dominated by the use of NbTi superconductor. This technology is well developed and the cost is determined by the MRI magnet market and cannot be expected to become much lower. Meeting the demanding magnet requirements for future applications will require development of new materials.

A. *Nb₃Sn*

Achieving fields above 10 tesla requires the use of A15 compounds, the most practical and available of which is Nb₃Sn. In a practical geometry, magnets based on Nb₃Sn technology should be able to exceed 14 – 15 tesla at 4.2 K. Although this material has been around for 40 years, its use and development has been hampered due to its intrinsic brittleness and strain sensitivity. The challenge for magnet designers lies in incorporating it into a realistic magnet where it is subjected to stresses that could exceed 150 MPa. The future need for higher fields has prompted an increased development effort and much recent progress has been made.

Funding for a new HEP Conductor Development Program was provided in January, 2000 [4]. This program is focused on industrial development, and is administered by LBNL. The purpose of this work is to develop a new, cost-effective superconductor for use in future accelerator magnets, with the following target specifications:

- J_c (noncopper, 12T, 4.2K): 3,000 A/mm²
- $J_{\text{engineering}}(12T)$: greater than 1,000 A/mm²
- Effective filament size: as small as feasible, while compatible with the J_c and cost-effectiveness requirements
- Process unit size: scaleable to greater than 100 kg and average piece lengths greater than 10,000 m in wire diameters of 0.3 mm to 1.0 mm
- Wire cost: less than \$US1.50/kA-m (12T, 4.2K)
- Short heat treatment times: maximum 400 hours; target 50 hours for wind and react magnets

This is envisioned as a multi-year program with two phases that may partially overlap. The first phase (2-3 years) is primarily an R&D program leading to an improved understanding of the factors that influence conductor performance and cost. Using the new knowledge gained from this research as a base, the program will evolve towards a fabrication scale-up phase where the performance and cost-effectiveness can be demonstrated on production-size quantities. This program has been underway for about one year, and has achieved considerable technical success. One of the key parameters, critical current density, has been increased from the 2000 A/mm² level to a world record 2600 A/mm² at 12 tesla.

B. HTS

High Temperature Superconductors have been under intensive study and development for some time. The properties of these materials make them interesting for applications requiring high fields and/or high heat loads, such as interaction region quadrupoles. However, their mechanical properties and cost are still major drawbacks. Until significant progress is made, these materials will probably only be considered for use in cases where performance is essential to meet operational requirements. One example is to investigate the recently discovered MgB_2 superconductor as a possible material for developing a high temperature transmission-line magnet.

IV. COLLIDER MAGNETS

A wide variety of magnet technologies are now in various stages of development, ranging in field from 2 to 15 tesla. A VLHC proposed by Fermilab utilizes both ends of the field strength spectrum in a staged scenario.

Table I is a representative list, including fully developed designs from the past and present as well as recent prototypes.

TABLE I.
Examples of accelerator dipole designs

Dipole Magnet	Coil Geometry	Max Field (T)
FNAL Superferric	Transmission line	2
TAC Superferric	Block	3
Magnet in Magnet	Transmission Line	4
RHIC	$\cos\theta$	4.5
HERA	$\cos\theta$	5.6
Texas A&M	Block	6.6
SSC 50 mm	$\cos\theta$	7.5
LHC	$\cos\theta$	7.8
LHC (1.9K)	$\cos\theta$	10.1
Tevatron	$\cos\theta$	5.5
U. Twente	$\cos\theta$	11.5
LBNL D20	$\cos\theta$	12.8
LBNL D20 (1.8K)	$\cos\theta$	13.5
LBNL RD-3	Common Coil	14.7

A. Superferric

There are several concepts being considered in the field range between 2 and 3 tesla. It is generally accepted that these magnets represent the lowest cost magnet option. Unfortunately, in terms of accelerator applications, the situation is not straight-forward. Low field rings must be extremely large in order to achieve the energies required for a significant step beyond the LHC. Iron-dominated magnets tend toward small bores, raising beam stability and vacuum issues. These and other related issues need concurrent study in order to effectively evaluate this application.

A superferric magnet for a proposed VLHC has been described in the VLHC Feasibility Study Report [5]. It has a

maximum field of 2 tesla generated by a 100 kA, superconducting transmission-line, Fig. 1.

A couple of alternative designs were discussed which offer more freedom in the choice of parameters. The Texas Accelerator Center (TAC) magnet was proposed for the SSC [6]. Several of these long magnets were built and successfully tested, Fig. 2. Relative to the FNAL transmission-line magnet, they have a larger bore (2.5 cm X 3.5 cm compared to 1.8 X 3.0 cm) and higher field, 3 tesla.

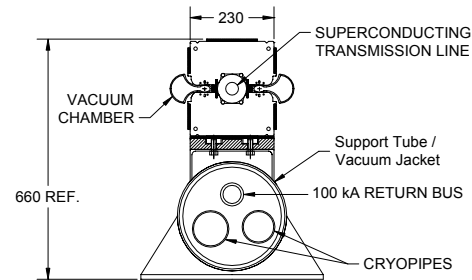


Figure 1. FNAL Transmission-line Magnet

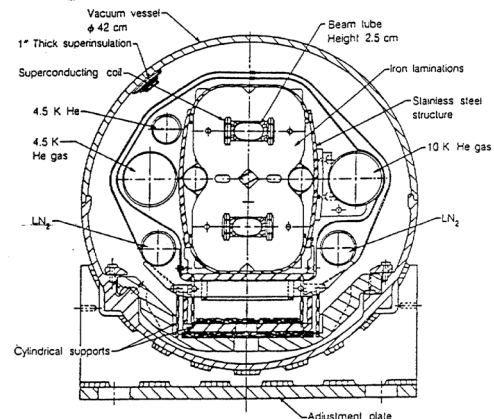


Figure 2. Texas Accelerator Center Superferric Magnet

The multiple current powering scheme employed to cope with saturation effects may provide a means of extending the dynamic range, allowing consideration of a first stage VLHC with 50 TeV center-of-mass energy in a smaller ring while still retaining the Tevatron as the injector. This magnet will require a more extensive cryogenic system and beam screen at the luminosities and energies under discussion. At the time of the SSC, the multiple power supply requirement was considered a drawback, but power supply technology has progressed significantly since that time, making the TAC magnet, or some variation of it, a possible candidate for an inexpensive collider dipole. Proceeding in that direction, a 3 tesla, cold iron, combined function magnet has since been designed by FNAL [7]. The main field is driven by a 160 kA transmission-line. Saturation effects are corrected via an 8 kA correction winding, Fig. 3.

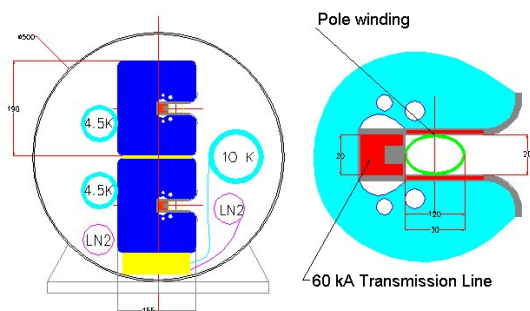


Figure 3. Three tesla, cold iron, combined function superferic magnet.

B. Medium Field

A small-bore, 5 tesla, NbTi magnet, based on the RHIC dipole was discussed at the Workshop. The RHIC dipoles have often been used as a benchmark to evaluate technology options for future colliders [8]. Medium field magnets allow more flexibility in the choice of machine parameters and overall may lead to a less expensive accelerator. It was generally agreed that magnets in this field range merit further detailed study.

C. High Field Dipoles

The natural trend in accelerator magnet development is towards higher fields, sometimes out of necessity and sometimes due to considerations of tunneling, logistics, infrastructure, etc. Consequently there is considerable activity in this area.

Aside from the challenges inherent in the construction of magnets using the brittle and strain sensitive materials required for high fields, other important issues come into play. The energies being considered for new accelerators along with the small arc-bend radii lead to significant synchrotron radiation loads. Because of the large filament diameters and high J_c of Nb₃Sn, magnetization effects are much larger than in NbTi magnets. As fields increase, cost increases as well. Magnet designs that meet cost reduction requirements will need to depart significantly from the present “conventional” designs now in use. These and other issues must be evaluated and compared with other options in the context of the proposed application.

1) Synchrotron Radiation

Future hadron colliders will produce several W/m/beam of synchrotron radiation power. The second stage VLHC, proposed by Fermilab, would produce 5 W/m/beam. This value is obtained with a peak proton energy of 100 TeV, luminosity of $2 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$, a circumference of 233 km and 10 tesla dipoles. Other possibilities with higher luminosity and smaller rings could have power levels greater than 20 W/m/beam. Unlike electron machines, this power must be extracted from a cryogenic environment.

At present there are at least two possible solutions to the problem of extracting the synchrotron radiation heat load from a cryogenic magnet; beams screens, such as those used for the LHC and photon stops that intercept the synchrotron radiation at the magnet interfaces [9].

Beam screens are limited to heat loads of about

30 W/m/beam because of the cooling channel requirements. This situation may be mitigated somewhat by making use of block coil designs that have free vertical space for additional cooling without increasing the bore diameter. For loads below 5 W/m/beam, the LHC solution works well. For higher loads, the temperature of the screen has to be raised along with the cooling channel size. For example, a room temperature, water cooled beam screen surrounded by an 80 K shield could be used. In determining the optimal design, the static heat load from the shield must be balanced against the dynamic load.

The photon stop has a potential advantage over the beam screen in that the synchrotron heat load can be extracted at room temperature. While these devices are frequently used in light sources and electron colliders they have not been used in a cryogenic environment. Critical issues of the photon stop design are primarily related to the surface power-density and secondarily to its impedance. There are also geometrical limitations to the use of photon-stops that impose limits on the combination of magnet aperture, length and ring radius.

2) Magnetization

The high current density and large filament diameters of Nb₃Sn conductor produce magnetization effects that are about a factor of 40 larger than for LHC. Several methods involving passive reduction of the effect through the addition of thin iron strips, either in the bore or within the coil are being investigated. In the case of a block-coil configuration, the coil geometry can be arranged to cancel a large fraction of the effect, Fig. 4 [10]. Another idea, incorporating a very thin ferromagnetic shield inside the bore, looks promising [11].

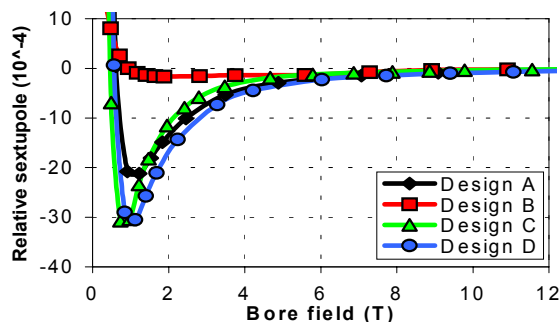


Figure 4. Comparison of magnetization sextupole for “A”- cosine theta, “B”- Common coil, “C” – Block coil and “D”- Common coil with auxiliary field-shaping coils.

D. High Field Magnet Programs

The recent success of a 14.7 tesla, Nb₃Sn dipole built by LBNL [12] has expanded the field range that can be considered for accelerator dipoles, Fig. 5. Other programs, working at slightly lower field levels, combine to generate a significant world-wide effort using Nb₃Sn and HTS conductors that will generate a solid technology base from which to develop magnets for future accelerators.

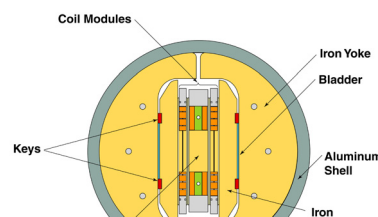


Figure 5. LBNL 14.7 Nb₃Sn, common Coil Dipole Cross section

1) Brookhaven National Laboratory

The primary goal of the magnet R&D program at BNL is to develop magnet designs and technology where high temperature superconductors (HTS) play a major role. The performance and availability of high temperature superconductors have reached levels that allow serious magnet R&D to be started. BNL is developing several designs (including the common coil design concept for VLHC) that take into consideration the brittle nature of high field conductors. They are based on racetrack coils with large bend radii, suitable for “React & Wind” technology. BNL is also building racetrack coil magnets with open midplane gaps for a neutrino factory storage ring. A new design, where ends provide skew quadrupole focusing, eliminates space wasted in the ends. In addition, the quadrupole magnets for VLHC interaction regions and an LHC interaction region upgrade are also being developed using the same general technology.

In addition to developing several new magnet designs, BNL is engaged in a rapid turn-around program to test many short HTS and Nb₃Sn coils based on cables and tapes. The performance of these HTS coils has been very encouraging so far. The next phase of the BNL program will be to make field quality measurements in magnets built with HTS coils and to test the HTS coils in a 12 T background field generated by Nb₃Sn superconductor.

2) CEA/Saclay

The Saclay group has been involved with Nb₃Sn for some time. They are currently applying this technology to the development of high gradient quadrupoles [13]. The model magnets are based on the design of the LHC arc quadrupoles. The 56 mm bore magnet is expected to have a gradient of

222 T/m at an operating temperature of 4.2 K. A cross section of the magnet is shown in Fig. 6. A unique feature of their test plans is to immerse the quadrupole in a solenoidal background field to simulate an application for TESLA.

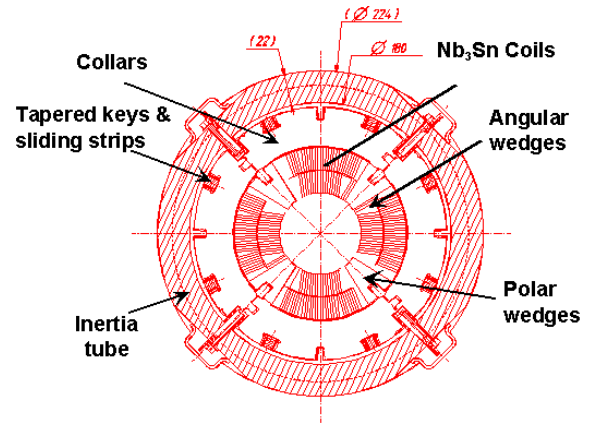


Figure 6. Nb₃Sn quad cross section

3) Fermi National Accelerator Laboratory

Arc dipole magnets are based on the common coil design and react-and-wind fabrication technique. This is regarded at this time as the most innovative and cost effective approach, although it requires significant efforts to prove it experimentally. Extensive R&D efforts in this direction are in progress at Fermilab, LBNL and BNL. Single-layer common coils with 19 and 25 kA nominal current were developed at Fermilab. There are also other magnet design approaches based on the traditional cos-theta (shell-type) coil geometry that allows both horizontal and vertical bore arrangements. These magnets based on two-layer and single-layer coils are being developed at Fermilab for the VLHC and meet the Stage-2 VLHC requirements, including operating field range, field quality, critical current and critical temperature margin, quench protection, etc. Due to the small bending radii in the cos-theta type coils, the wind-and-react technique is necessary in order to avoid excessive degradation of the cable critical current during coil winding. These coils can be placed much closer to each other, especially in the horizontal bore arrangement, reducing the iron yoke size and the total magnet size, weight and cost.

4) CERN/University of Twente

The magnet group at the University of Twente is a pioneer in the development of Nb₃Sn magnets. The group substantially exceeded the 10 tesla barrier with a Nb₃Sn dipole in 1995 [14]. In collaboration with CERN, the group is now engaged in the development of a 10 tesla, 88 mm bore, Nb₃Sn dipole for a possible upgrade for the low field LHC beam separator dipoles [15], Fig. 7. The group has been especially active in the development of power-in-tube (PIT) superconductors [16].

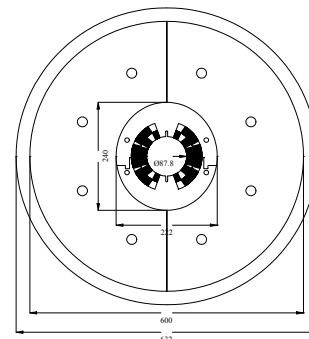


Figure 7. CERN-U. Twente D1 Cross section

5) Lawrence Berkeley National Laboratory

The LBNL superconducting magnet program is primarily directed towards development of high field magnets for future accelerators. The desire for simplicity, along with advances in fabrication techniques and materials encourage a return to simple racetrack coil geometries that have advantages in support structure design and fabrication.

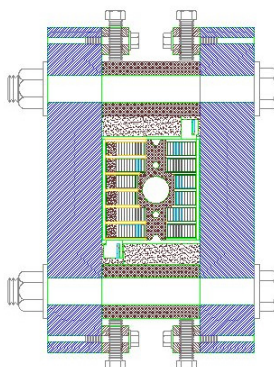
In particular, the group is concentrating on the common coil configuration. The design concept consists of a pair of racetrack coils shared between two apertures, producing fields in opposite directions. This geometry is intrinsically suited for a collider, but modifications of this design can be used for single-aperture applications as well. In addition to pushing limits of high field magnets, the group is building an extensive series of smaller magnets in the field range of 11 – 12 tesla for specific studies; conductor evaluation, mechanical support structures and fabrication techniques.

6) Texas A&M University

The Texas A&M magnet program is based on interdependent avenues of approach to a future machine magnet ring based on high field, high current density, wind and react, and *internally stress managed* windings. The first avenue of approach is that of extensive design studies, which are concentrating at the present time on several tasks, one of which is a block coil variation in the 14 – 16 tesla range with bore sizes of 30 to 40 mm diameter. These designs are based on race track coils which contain internal high strength (Inconel 708, and titanium) support structures to limit stress integration and intercept it across the winding packages. Other design concepts are under consideration, including a “Tevatron Tripler”, quadrupoles with gradients up to 425 T/m and small bore VLHC designs.

The group has assembled and tested a set of block coils. The windings utilized NbTi conductor, but included all the

material except the A15 superconductor and most of the techniques necessary to produce an A15 conductor winding (i.e. Nb₃Sn..) with a “wind & react” procedure as well as the stress management internal structure, Fig. 8. This prototype performed very well, achieving a “short sample” of 6.7 tesla at 4.3K in six spontaneous quenches [17]. The present prototype design under construction is a 12 – 13 T “Tevatron Tripler” type Nb₃Sn winding with a single aperture and an



additional inter-layer ferric plate for low field harmonic correction.

Figure 8. TAMU-1, NbTi Common Coil Magnet

V. PERMANENT MAGNETS

Progress in the magnetic properties of permanent magnet materials has been impressive. Materials such as Sm₂Co₁₇ and new types of Nd₂Fe₁₄B have a maximum energy product of 240 – 400 kJ/m³. High field magnets made from these materials have applications as high gradient, adjustable quadrupoles for the NLC, injection line, correctors and Lamberts for a VLHC and damping ring magnets and wigglers. R&D is directed towards improving the thermal and radiation stability, adjustable strength with high magnetic center stability and hybrids for improved stability and use as accelerator magnets. A combination of declining costs and improved materials has made permanent magnets competitive with conventional and superconducting magnets in many applications.

Perhaps one of the most significant steps that lead to the present interest in permanent magnets is the recent data from the Fermilab Recycler where extensive use of hybrid permanent magnets was implemented. The term hybrid refers to the use of permanent magnet material to excite the iron poles that shape the field. Quadrupole, dipole and combined function magnets have been fabricated, installed in the Fermilab Main Injector tunnel and commissioned with beam [18].

A joint effort by Fermilab, SLAC and LBNL was initiated about 2 years ago to develop adjustable quadrupoles for the Next Linear Collider (NLC) and has resulted in five models for use in the Main Linacs of the NLC [19]. The initial design used electromagnets. The greatest challenge in this application is to develop a magnet with a field variability of 20% with a quad center stability of 1 micrometer. Of the four permanent magnet quad models tested so far a rotational quad design gives the best result for the stability of the quad center during strength change [20].

An interesting idea for increasing the dynamic range of the FNAL Transmission-line magnet was proposed by M. Kumada of NIRS [21]. The concept, dubbed Magnet in Magnet (MiM), involves the insertion of a compact Halbach type, 2.1 tesla permanent magnet dipole into both air gaps, Fig. 9. Excited in a bipolar mode, the resultant field can be made to vary from 0.1 tesla to 4.1 tesla. The diameter of the PM inserts is roughly 100 mm and the necessary excitation current is about 250 kA. The field stability of the MiM magnet is controlled by power supply feedback.

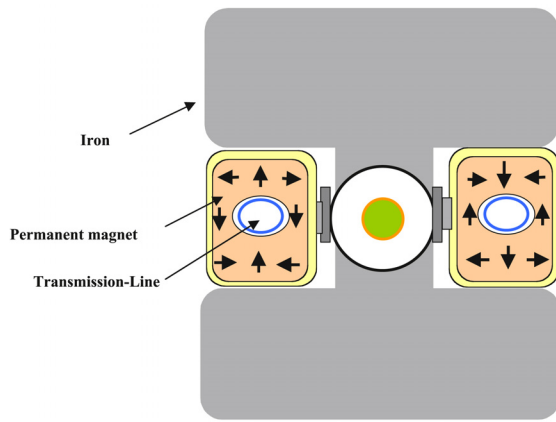


Figure 9. Magnet in Magnet Transmission-Line Concept

VI. IR QUADRUPOLES

Particle beams are brought into collision through the use of interaction region magnets. High gradient quadrupoles represent the greatest challenge in terms of performance. Cost in this case, is not the overwhelming issue. High fields and very large heat loads require either innovative use of Nb₃Sn or HTS, which still needs to be proven to be a viable material.

A. General Requirements for IR magnets

The focusing requirements and the presence of interaction by-products make the operational requirements more stringent than for the arc magnet counterparts. The following issues have been identified as important to interaction region magnet design:

1) High gradient/field and large aperture

As these magnets form the final focus, they are located as close as practically possible to the interaction regions. This requires high gradients to achieve the required β^* with a limited focusing lever arm. The large aperture is required to accommodate absorbers in the beam pipe to intercept the large radiation/heat deposition due to interaction debris.

2) Excellent field quality

This is driven by the crossing angle and luminosity requirements for the interaction point.

3) High radiation environment/heat deposition

The proximity of the magnets to the IP puts a significant radiation load on the magnet. For the LHC, ~900 Watts/side of debris is generated at nominal luminosity and energy. Of this, 200 Watts is deposited in the cryogenic system through the beam tube and beam tube liner. The energy deposition scales linearly with the beam energy, so in the proposed Stage-1 VLHC, the cryogenic heat load increases to 600 W/side.

4) Alignment and mechanical stability

Misalignment leads to luminosity loss, causes the beam to populate off-axis areas of the aperture and thus become susceptible to harmonic errors that can lead to a reduction in dynamic aperture. Typical transverse alignment goals are 300-500 micrometers, 1-2 mm longitudinally, 1 milliradian in roll and 100 microradians in pitch and yaw.

B. IR Magnet Development

The IR quadrupoles for the Tevatron, RHIC, and LHC are made from Rutherford-style NbTi cables. The 70 mm aperture LHC inner triplet quadrupoles operate in superfluid with a peak operating gradient of 215 T/m. Future accelerator applications will require a combination of higher gradient, possibly larger aperture and higher heat loads. This means building magnets with Nb₃Sn or High Tc materials.

A proposed upgrade for the LHC IR's is an excellent opportunity to use Nb₃Sn technology for a production series of accelerator magnets. The experience from all phases of the magnet production, from cable procurement through construction and test will be invaluable for the VLHC program.

VII. MAGNETIC MEASUREMENTS

Magnetic measurements are an essential part of a magnet R&D program. Some magnets will only need an extension of present techniques; others will require a certain amount of development of new measurement tools.

The CERN measurement group has been very active in main arc dipole and quad measurements for LHC; they have been developing probes using ceramic materials which can be used in cold bore measurements [22].

New measurements techniques will need to be developed to cope with extremely long lengths (up to 65 m) and low and high field magnets with bore diameters of 20 mm. Combined function magnets with gradient profiles of 5 – 9% are also being considered.

For larger bore, high field magnets, the techniques developed for the LHC and older types of magnets will be sufficient. That is, a combination of rotating coils to measure the harmonic content with stretched wire systems to measure integral strength and alignment. Apertures on the order of 40 mm may present some challenges for a rotating coil system, since lower coil radius will result in reduced signal size. The effective aperture size for a probe may be further reduced by the presence of a beam screen. This may be mitigated by the very large signal one will expect for high fields.

Fermilab has been very active in permanent magnet technology since the Recycler development, which used thermally-compensated Sr-ferrite ceramic magnets, [23]. Measurements have focused on the severe alignment requirements of these magnets (~1 μ m). A single stretched-wire technique has been successfully used. Measurement precision using existing stages is on the order of a few micrometers. Further investment in high accuracy stages will be necessary to achieve the measurement goals.

VIII. SUMMARY

Magnet designs in the 10-15 T range require a high field conductor, and Nb₃Sn presently offers the best combination of performance, availability, and cost. In addition to improvements in current density, R&D is continuing to meet the other technical goals, such as reducing the effective filament size in order to reduce field distortion at injection. However, lack of adequate testing facilities for these new, high current density conductors is hampering further development.

Due to recent advances, magnets with fields in the range of 2 – 15 tesla can be considered for a variety of applications. However, the time and resources required to develop the technologies vary significantly. For example, low-field superferic magnets such as the FNAL Transmission-line magnet or the Texas Accelerator Center (TAC) magnet could be brought into production in less time than it would take to dig a tunnel for a new machine. High field magnets based on Nb₃Sn would require longer development time, on the order of a decade, depending on funding levels.

A large fraction of the magnet R&D resources, including the large laboratories, CERN, Fermilab and KEK are focused on the LHC. The remaining resources are still able to pursue a significant subset of the major R&D issues. But, given the relative importance of magnet sub-systems, either as significant cost drivers and/or providing a critical function, the current level of R&D effort is disproportionately low if one is considering a successor to the LHC in a timeframe on the order of two decades. For example, development work on medium-field magnets as a VLHC option, is non-existent. In the case of other possibilities, most notably high field magnets, progress towards achieving a technological base from which to launch a development program has been hampered due to lack of adequate support. Realistic evaluation of the broad range of magnet technologies, ranging from permanent magnets to high field, superconducting dipoles, requires a more aggressive program. The formula for success requires a substantial increase in development activity along with an increase in collaboration (sharing lessons learned and facilities) between magnet programs worldwide. An integrated approach, combining input from accelerator physicists, and evaluated using a standard cost model, is necessary to arrive at a cost/performance optimized design. The magnet programs need to work closely with accelerator physicists to push all parameters to the limit and arrive at the most cost-effective combination of magnet design and machine performance. There has been informal activity in this direction, for example, at the VLHC Workshops, but there is a need to formalize it in a more coherent way.

At the Snowmass Workshop it was suggested that the RHIC model be generalized and used as a basis for design comparisons. The very successful VLHC Design Study is an excellent example of the combined approach (and effort) needed to evaluate accelerator/magnet options and should be expanded to include other possibilities and parameters.

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X. REFERENCES

- [1] Reports of the Snowmass Working Groups can be found at www.snowmass2001.org
- [2] L. Rossi, "State-of-the-Art Superconducting Magnets," these proceedings. to be published in the proceedings of the 17th International Conference on Magnet Technology (MT-17), Geneva, June 2001.
- [3] D. Fisher, et al, "Successful Partnership between Brookhaven National Laboratory and Northrup Grumman Corp. for Construction of RHIC Superconducting Magnets," *IEEE Trans. on Applied Superconductivity*, Vol. 10, No. 1, 183, March 2000, pp. 183-187.
- [4] R. Scanlan et al, "Development of Cost-Effective Nb₃Sn Conductors for the Next Generation Hadron Colliders," to be published in the proceedings of CEC/ICMC, Madison, Wisconsin, 2001.
- [5] P. Limon, et al, "VLHC Feasibility Study," Fermilab, www.vlhc.org, June 1, 2001.
- [6] F. R. Huson, et al, "Superferic Magnet Option for the SSC," *IEEE Transactions on Nuclear Science*, Vol. NS-32, No. 5, October, 1985.
- [7] V.S. Kashikhin, et al, "Superconducting Superferic Dipole Magnet with Cold Iron Core for VLHC," to be published in the proceedings of the 17th International Conference on Magnet Technology (MT-17), Geneva, June 2001.
- [8] E. Willen, "Superconducting Magnets," INFN Eloisatron Project, 34th Workshop, "Hadron Colliders at the Highest Energy and Luminosity," Erice, Sicily, November 4 – 13, 1996.
- [9] P. Bauer, et al, "Synchrotron Radiation Issues in the VLHC," to be published in the proceedings of the *IEEE Particle Accelerator Conference*, Chicago, June 2001.
- [10] V. V. Kashikhin and A.V. Zlobin, "Correction of the Persistent Current Effect in Nb₃Sn Dipole Magnets," *IEEE Trans. on Applied Superconductivity*, Vol. 11, No. 1, March 2001, pp. 2058-2061.
- [11] S. Caspi, "Reduction of Magnetization Induced Harmonics in Superconducting Magnets," Lawrence Berkeley National Laboratory, SC-MAG-691, October 1999.
- [12] R. Benjegerdes et al, "Fabrication and Test Results of a High Field, Nb₃Sn Superconducting Racetrack Dipole Magnet," to be published in the proceedings of the *IEEE Particle Accelerator Conference*, Chicago, June 2001.
- [13] A. Devred et al, "Development of a Nb₃Sn Quadrupole Magnet Model," *IEEE Trans. On Applied Superconductivity*, Vol. 11, No. 1, March 2001, pp. 2184-2187.
- [14] A. den Ouden et al, "An Experimental 11.5 tesla Nb₃Sn LHC type of Dipole Magnet," *IEEE Trans. Mag.* Vol. 30, 1995, p. 2320.
- [15] A. den Ouden et al, "A 10 T Nb₃Sn Model Separator Dipole magnet for the CERN LHC," proceedings of MT-15, 1997, pp. 137-140.
- [16] A. den Ouden et al, "Application of Nb₃Sn Superconductors in High-Field Accelerator Magnets," *IEEE Trans. On Applied Superconductivity*, Vol. 7, No. 2, June 1997, pp. 733-738.
- [17] C. Battle et al, "Testing of TAMU 1: A Single-Aperture Block-Coil Dipole," to be published in the proceedings of the *IEEE Particle Accelerator Conference*, Chicago, June 2001.
- [18] G.W. Foster et al, "Permanent Magnet Design for the Fermilab Main Injector Recycler Ring," Proc. of the *IEEE Particle Accelerator Conference*, Dallas, Texas, May 1995, pp. 1298-1300.
- [19] J. DiMarco et al, "Adjustable Permanent Quadrupoles Using Rotating Magnet Material Rods for the Next Linear Collider," to be published in the proceedings of the 17th International Conference on Magnet Technology (MT-17), Geneva, June 2001.

- [20] V.S. Kashikhin et al, "Rotational and Magnetic Shunt Permanent Magnet Quadrupoles with Variable Magnetic Strength," to be published in the proceedings of the 17th International Conference on Magnet Technology (MT-17), Geneva, June 2001.
- [21] M. Kumada, "National Institute of Radiological Sciences," Anagawa, Japan, personal communication, 2001.
- [22] J. Billan et al, "Twin Rotating Coils for Cold Magnetic Measurements of 15 m Long LHC Dipoles," *IEEE Trans. On Applied Superconductivity*, Vol. 10, No. 1, March 2000, pp. 1422-1426.
- [23] W.B. Fowler et al, "Experience with the Procurement of Ferrite and Temperature Compensator for Permanent Magnets for Accelerators," *Proc. of the IEEE Particle Accelerator Conference*, Vancouver, Canada, May 1997, pp. 3254-3256.